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TECHNICAL REPORT 3861

INITIATION OF SECONDARY EXPLOSIVES
BY MEANS OF LASER RADIATION

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EDWARD G. KESSLER

MAY 1969

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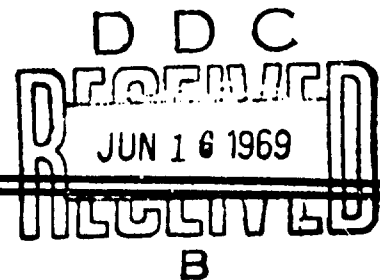
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Technical Report 3861

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OBJECT

To investigate the feasibility of using laser radiation to detonate secondary explosives and to determine the parameters affecting this detonation.

ABSTRACT

An experimental investigation was conducted to determine the feasibility of directly detonating secondary explosives by means of radiation from a ruby laser (6943A). The secondary explosives included PETN, HMX, RDX, and tetryl. Most of the effort was devoted to a statistical evaluation of the initiation energy required for PETN. For the most part, powdered explosives were used; however, a limited effort also was expended on large single crystals. The use of a light guide as a means of transporting energy was also examined. It was established that although a highly sensitive mixture can be detonated through a light guide, the attenuation of the radiation is too great to make this method practical for secondary explosives. A bivariate dependence of the probability of initiation on both power and energy is indicated. The effectiveness of the experimental techniques of power evaluation was, however, limited by the speed of the equipment used.

INTRODUCTION

Modern technology, especially as applied in the military sector, would welcome the ability to safely detonate secondary explosives directly, i.e., without the need of a primer. Ideally, the stimulus would not only be reliable, but would provide a degree of safety higher than, e.g., that of some of the primers presently used, which are very sensitive to heat and friction, making them extremely dangerous to work with. With the development of efficient lasers, a new stimulus has been made available. The laser seems to lend itself well to such an application. The focusing properties of its monochromatic radiation make it capable of producing high temperatures, while intense shocks may be produced with the higher-power Q-switched lasers. Besides being safer, such a laser system also would be more reliable than one using a primer, since arming devices, which might result in mechanical or electrical failure, would not be necessary.

The ability to detonate reliably a secondary explosive by means of laser radiation would also be extremely useful in explosive sensitivity tests. In the production of secondary leads, boosters, and chargers, reliability tests presently are performed only in conjunction with detonators involving a primary explosive. Detonators themselves display more than a little variation in energy, and good sensitivity tests therefore are difficult. With the use of a laser system, precise energy input measurements would be possible, and consequently extremely accurate sensitivity measurements could be obtained.

Having established the feasibility of laser initiation of primary explosives in previous work (Ref 1), it is the objective of this present endeavor, firstly, to determine whether or not secondary explosives can be detonated in a similar manner and, secondly, to define and describe the conditions under which reliable detonation can be achieved.

The present investigation was limited to the radiation of a ruby laser. Free-running as well as Q-switched techniques were used. The selection of secondary explosives was influenced only by the relative preponderance of their present use by the military. Within this frame of reference, PETN, tetryl, HMX, and RDX were the explosives selected.

Many variables had to be considered. Characteristics such as grain size, density, confinement pressure, and relative humidity are just some of those associated with the explosive. Variables characteristic of the laser are power, energy, frequency, etc. Only the variations of the parameters which would seem to have the greatest effect on our results were considered. Power, energy, and pressure were regarded as variables, while characteristics such as temperature and grain size were assumed to be constant.

A thorough investigation of the laser initiation of explosives would include a broad effort to understand the mechanism by which the light energy is transported into the initiation of the explosive and the subsequent growth into an explosion. Such a description has yet to be fully developed for the stimuli presently used (Ref 2). It therefore should be understood that it was not the primary objective of this program to investigate the coupling mechanism, but rather, first to establish feasibility, and second, to set some limits on the conditions necessary for reliable detonations. This initial work would consider energy transport only in an attempt to understand its basic nature, be it thermal (Ref 3), electronic, or mechanical. The primary purpose of this effort, which followed an experimental approach, was to establish feasibility and justification for continuing programs of this nature.

EXPERIMENTAL PROCEDURE

The laser used in these experiments was a pulsed ruby rod (6943A), with a plano total internal reflectance configuration. The ruby rod had a diameter of 5/8 inch and a length of 6 inches. A 50% reflecting mirror at the front end was found to give excellent lasing action. Pumping action was provided by two FX 47 xenon flash lamps manufactured by Edgerton, Germenhausen and Grier. With the configuration described above, Q-switching was possible only from the front end of the rod. In cases where Q-switching was desired, a cell filled with a passive liquid Q-switch solution (Maser Optics, Inc.) was placed in the beam between the front end of the rod and the external 50% mirror.

Although a passive liquid provides excellent switching, it is, in certain respects, less reliable than other means of Q-switching such as Pockel cells, rotating mirrors, etc. First, the liquid is self-activating and cannot be controlled as easily as some of the other devices. Second, the switching characteristics of the liquid depend on both the concentration of the liquid and the energy output of the laser. This makes it more difficult to obtain a good single pulse when using a liquid switch. However, if these facts are allowed for, and if proper monitoring is used, the liquid solution can give good results.

The laser head was aimed to fire through a hole into an explosive barricade. A front surface mirror was placed in the barricade to reflect the beam down onto the explosive sample (see Fig 1). The mirror was used to displace the laser head from a direct line of sight of the explosive and thus protect the laser from flying fragments.

A hydraulic ram was placed under the test sample. Its purpose was to compress the explosive inside a die against a glass block. The glass block allowed the laser light a path to the sample while keeping the sample under pressure.

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To monitor energy, a glass beam splitter was placed outside the barricade in the laser path at an angle to reflect 5% of the incoming beam into a thermopile.

For initiation time measurements, a DuPont "Corfon" light guide was run into the barricade. The interior end was pressed against the glass block. There it conducted both the light of the laser striking the test sample and the light of the detonation to an EG&G "Lite Mike" (rise time 5 nanoseconds (ns)). The resultant output was indicated on a Tektronix 585 oscilloscope. The term "initiation time" was defined as the time between the arrival of the first laser spike at the target and the onset of the detonation. When necessary, a lens was inserted in the path of the laser beam so as to focus it onto the top surface of the test sample.

Energy measurements were taken by allowing the beam reflected from the beam splitter to fall onto a ballistic thermopile, which was calibrated to include losses introduced by lenses, mirrors, and other sources of light attenuation which might be present in the beam path, i.e., to give the amount of energy actually hitting the explosives. Results from this thermopile are reliable within ±5%.

EXPERIMENTATION

Preliminary Trials

Our first attempts were designed only to determine the feasibility of laser initiation of explosives. These first experiments consequently were not designed to prove or disprove any detailed or refined considerations, but were rather a gross effort to determine whether or not secondary explosives could be detonated at all by using a laser. We fired at a pyrotechnic mixture (consisting of 50% KNO_3, 25% nickel powder, and 25% aluminum powder), HMX, PETN, and tetryl.

The laser power supply had a capacity of 1600 microfarad (mfd) giving to the laser cavity an energy input of 7200 joules when fired at 3000 volts. These first experiments were conducted with the laser fired at 3000 volts, since this was well above the lasing threshold of our cavity, assuring us of lasing on each shot. The laser output (0.1 - 20 joules, depending on both the mode of operation and the temperature of the rod) was focused onto the sample surface using a lens of 9 cm focal length. These first attempts gave the following results:

The pyrotechnic mixture responded readily to the laser radiation. With the laser operating in the free-running mode, it was found that this mixture had an average initiation threshold of approximately .0053 joule per square millimeter exposed (Table 1). When the laser mode was changed to Q-switch, it was found that the initiation threshold of this same mixture was lowered below the measuring limits of our instruments. The pyrotechnic mixture was also initiated by focusing the laser beam into a plastic light guide and placing the other end of the light guide in the mixture. It should

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be mentioned here that none of the secondary explosives could be detonated using this light guide method. If, however, the secondary powder was mixed with the pyrotechnic mixture, the light guide proved successful in achieving detonation. These few initial attempts at using a light guide as a means of transporting energy seem to indicate that the guide attenuates the radiation to a point where it is no longer effective as a stimulus for the explosive.

No detonation could be excited in the secondary explosives as a loose powder by either the free-running or the Q-switched laser. By adding a black coloring agent to the powder, however, we achieve at least partial consumption. This coloring agent probably had the effect of inducing hot spots which in turn increased the probability of initiation. Consumption by using a coloring agent was completed only when the sample was compressed, applying a pressure of 7500 psi. This confinement pressure increased the sensitivity of the secondary powders enough to cause detonation even without the aid of a coloring agent. This can be explained by the fact that initiation by adiabatic compression of trapped gas is more probable at higher confinement pressures. PETN confined at 7500 psi would reliably detonate. At this same pressure, tetryl would partially detonate; however, when the pressure was increased to 13,500 psi, reliable detonation was achieved. HMX was unaffected at 7500 psi, but at 13,500 it showed reliable sensitivity. In all cases, the probability of response was much increased when the secondary explosive was radiated by a Q-switched rather than by a free-running laser. This, combined with the fact that the Q-switched laser has considerably less total energy than a free-running laser (see Fig 2), constitutes a strong indication that a functional relationship between threshold of detonation and applied stimulus is not simply energy dependent. It is recalled that the pyrotechnic mixture mentioned earlier also displayed this behavior.

Large Single Crystals

Several secondary explosives (PETN, RDX, tetryl) were available in large single-crystal form. These were fired upon, using the Q-switched laser, with no apparent result. If, however, the crystal was placed in an inert powder and then compressed, applying a pressure of 8000 psi in such a manner that one flat side of the crystal was visible through the glass plate (see Fig 1), its sensitivity was increased enough to cause detonation. In these experiments the light was focused within the crystal using a 9-cm-focal-length lens. A full explanation of these observed facts would no doubt require an extensive number of experiments with crystals. Such an investigation would indeed be of interest, and even necessary, for a full analysis of the laser initiation of explosives. Realizing the great number of experiments which might be required, it was decided to postpone an investigation of crystals to a future date, and to limit the present effort to secondaries in powder form, specifically PETN (Ref 4). However, even without a further investigation, the crystalline behavior seems to give evidence to justify the following description:

· The conditions under which a detonation will occur are varied, depending upon such things as the density of explosive, its absorption properties, its relative confine- ment, etc. For instance, in the case of the loose secondary powder, which was insensi- tive to the radiation, addition of a black coloring agent increased its absorption po- tential enough to cause partial consumption. A further increase in sensitivity was achieved by confining the powder. Thus the physical condition of the explosive, and especially the density and confinement pressure of the charge, largely influence its sensitivity. We define density in the normal sense of mass per volume, confinement pressure as the pressure exerted on the sample at the moment the laser strikes. The exact influence that density exerts on sensitivity to laser adiation is not known. However, we have been able to show that increasing confinement pressure greatly in- creases the explosive sensitivity.

In the case of a large single crystal, on the other hand, the probability of initiation by adiabatic compression of trapped gas would not increase by confining the crystal under a pressure of 8000 psi. Any increase in sensitivity would probably be due to the following circumstances: If one assumes a hot-spot initiation, then it is, in the case of secondary explosives which have melting points below their initiation points, highly improbable that the hot spot would have its origin on the explosive molecule; rather, it would be nucleated on some impurity or imperfection of the explo- sive. For a large single crystal, this would most likely be located at the surface, and if the crystal is unconfined, any initial energy released there would be free to escape. In the case of a confined crystal, this is less likely, and consequently higher pres- sures and temperatures are achieved, increasing the probability of detonation. Our initial conclusion derived from the limited work done with crystals thus far is that a crystal, although extremely dense, will not detonate by laser radiation unless properly confined.

Initiation Threshold for PETN

From initial experimental work we learned that, to get meaningful and reproducible results, the control and monitoring of all experimental parameters, such as grain size, temperature, pressure, and energy, is of extreme importance. In some cases this pre- sented no real problem, e. g., temperature and pressure could be kept reasonably con- stant. For grain size an attempt was made to acquire a relatively pure and uniform ex- plosive powder. Properties of the radiating source such as power, energy, and fre- quency are particularly important, since it is the functional dependence of detonation on these parameters which is under investigation. Frequency will remain constant for all of these experiments at 6943A.

Our initial effort was to define the energy sensitivity of the explosive. Since there is no exact go/no go point, a statistical evaluation of the results had to be undertaken. The energy threshold should be of the form shown in Figure 3.

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In order to adequately define the cumulative distribution function from the data, it is important that energy be varied enough to assure in the data energy levels that provide 100% detonations, and those that fail to produce detonation. If these limits were not reached, the threshold curve could not be adequately defined. In attempting to define the energy threshold, we often exceeded the limits of sensitivity of our measuring equipment without covering the lower bounds of the threshold curve.

The following sets of experiments were carried out in an attempt to cover completely the energy threshold curve: If the energy was varied over an order of magnitude, yet still failed to cover the threshold curve, the deviation was considered too great to provide useful information. In this case, a parameter was varied for the next series in an attempt to reduce the deviation.

The first set of experiments was run at 7,500 psi, with the PETN placed inside the focus of a 9-cm-focal-length lens, and the beam covering an area of 2 sq cm. It was felt that although there might be local dissimilarities in sensitivity due to variations in grain size, the differences should average out, and we should get better consistency, by covering a large number of grains with the beam. However, the incident energy was varied from .09 to 1.95 joules without covering the threshold.

We then switched to focusing the beam on the surface, using the 9-cm-focal-length lens. The area of illumination at the target was 2 sq mm, and we covered an energy range from .013 to .055 joule, with erratic results.

Recalling that tetryl had failed to detonate at 7500 psi, and had been initiated at 13,000 psi, we decided to increase the confinement pressure on our PETN samples. Our hope was to reduce the spread of initiation energies previously encountered. With this increase in pressure, reliable detonations were achieved at a somewhat lower input.

When the data provided a reasonable coverage of the curve, we used a maximum likelihood method to estimate the mean (μ) and the standard deviation (σ) of the curve.

The equation of the probability curve is

$$\hat{P}(E) = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{E} \exp\left[-\frac{(t-\mu)^2}{2\sigma^2}\right] dt$$

The best estimates of μ and σ are chosen according to the maximum likelihood method. In this procedure they are taken to be those which maximize the quantity

$L = \prod_{i=1}^{s} \hat{P}_i \prod_{j=1}^{n-s}(1 - \hat{P}_j)$, where L is the maximum likelihood estimator, $\hat{P}_i$ is the probability

of success in the ith trial, and s is the number of successes, while $(1 - \hat{P}_j)$ is the probability of failure in the jth trial and n–s is the number of failures. A full analysis of this method has been given by Golub and Grubbs (Ref 5), and Kessler (Ref 6) has adapted it in a manner suitable for use on a high-speed computer.

The data (Table 2), while more consistent than our previous results, indicate that a spread of more than an order of magnitude was necessary to completely define the threshold curve.

With the accumulation of data and their statistical evaluation, the reasons for our large deviations of threshold energy were becoming evident. First, our belief that initiation was functionally related to energy input, with little dependence on variations in power, seemed disproved. Statistical results became more consistent if approximate values of power levels were injected as a variable along with energy.

The free-running laser was giving us unequally spaced spikes of more or less randomly distributed power levels. Also, as the initiation time varied, we could not accurately estimate which portion of the laser train was responsible for the actual detonation. Our consequent need to know the exact power output of our laser caused us to switch from a free-running to a Q-switched mode. For an exact measurement of the power level, knowledge of the duration of each energy pulse would be required. With our present equipment, exact measurement of such ultrafast pulses (< 50 ns) was impossible. Approximations were used, one of which was based on the assumption that our newly installed liquid Q-switch was providing a clean single pulse.

The deviation was indeed reduced by use of the Q-switched laser (Table 3). We have no accurate estimate of the power involved. It was discovered during the tests that the Q-switching solution would deteriorate with time and produce several giant spikes, which could introduce considerable error in the data.

It is evident that the energy threshold is reduced by the increased power of the Q-switched spikes; consequently, it appears that our thresholds are a function of power as well as energy. However, our experiments could not accurately take into account the power relationship.

A good evaluation of the power threshold will require an ultrafast detector as well as a scope of similar rise time. Such equipment is now on order. We also hope to be able to resolve any fine structure associated with the Q-switched pulses, an operation which is beyond the capabilities of our present detection system. If such fine structure exists, a knowledge of its form would improve power estimates.

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DISCUSSION

It is our contention that the detonation of explosives is a function of both power and energy. At this time we cannot fully resolve the power, since the rise times are beyond the capabilities of our present equipment. In the analysis of present data, we get a variation greater than an order of magnitude in the apparent threshold energies. We believe that if we were able to hold power at a constant value, the energy-threshold deviation would be reduced to a reasonable value.

We expect that if we were able to monitor both power and energy in our coverage of the threshold, we would find a normal bivariate distribution of the form

$$\hat{P}(E,P) = \frac{1}{2\pi\sigma_1\sigma_2\sqrt{1-\rho^2}} \int_{-\infty}^{P}\int_{-\infty}^{E} \exp\left[-\frac{1}{2(1-\rho^2)}\left(\frac{(E'-\mu_E)^2}{\sigma_E^2} - 2\rho\frac{(E'-\mu_E)(P'-\mu_P)}{\sigma_E\sigma_P}\right.\right.$$
$$\left.\left.+\frac{(P'-\mu_P)^2}{\sigma_P^2}\right)\right] dP' \, dE'$$

where σ_E^2 is the variance of E, σ_P^2 is the variance of P, and ρ is the correlation coefficient between P and E.

The cumulative distribution function of $\hat{P}$ is of the form shown in Figure 4. There is a minimum rate of application of energy required, below which detonation will not take place. Above the threshold, the amount of energy necessary for initiation decreases as power increases. Finally there should be a point where further increases in the rate will not reduce the energy requirement.

An energy-power relationship of this form has been obtained using various sources of power and energy (Ref 7) such as stab initiators, hot-bridgewire electric initiators, and conductive-mix electric initiators. It is reasonable to expect that such a relationship should be found for our source of energy input.

We feel that we can adapt an analysis similar to the monovariate case to the bivariate distribution to find optimal estimates of the five parameters involved, when power is accurately measured.

A further indication of the power dependence of initiation is evidenced by the results obtained in respect to initiation times. PETN was found to have an initiation time ranging from 50 to 100 microseconds when radiated by a free-running laser. When the laser was Q-switched to give higher power output, this initiation time decreased to below 25 microseconds.

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CONCLUSIONS

With the experimental work thus far completed, we feel very strongly that the direct initiation of secondary explosives is not only possible, but also functionally practical. Such a system has a potential, not only in explosive devices, but also in explosive-sensitivity analysis and experimentation. At this point we draw no conclusions concerning the operating mechanism of this type of initiation, except to note that most of the results presented in this report would fit into a thermal initiation theory.

Although we did not conduct any pertinent investigations in depth on variation of the radiating source, such as second harmonic generation, to effect absorption, or any variation of the explosive itself, such as grain size, ambient temperature, or introduction of foreign material, we feel that the initiation of secondary explosives is dependent on both power and energy of the radiating source.

Reliable detonations have been achieved with energy inputs as low as .025 joules/sq mm. There is no reason to doubt that this value still can be reduced since the bivariate distribution predicts lower energy requirements for high power inputs.

With the ultrafast rise time equipment which we expect to have shortly, we shall attempt to define the exact form of this bivariate distribution. The natural course to follow after that would be to investigate some of the many variables mentioned earlier and to see how they affect this distribution.

A light guide can be used as a means of transporting energy to produce reliable detonations; but the secondary will only detonate if mixed with a more sensitive pyrotechnic mixture. There is, however, the possibility that second harmonic generation may increase the total absorption of the secondary explosive enough to make initiation through a light guide possible, and obviate the need for a pyrotechnic mixture.

RECOMMENDATIONS

Since all the theories and information applicable to conventional stimuli might have to be investigated for laser initiation., experimental possibilities involve enough work to keep investigators busy for years. Problems such as initiation by the adiabatic compression of trapped gas (Ref 8), hot-spot theory, addition of a suitable grit to induce hot spots are just some of the many avenues open to the investigators. Since nearly all secondary explosives begin to absorb appreciably only at a point below 3500A, while available laser radiation does not approach the ultraviolet, investigations involving second harmonic generation might be particularly interesting. Dielectric breakdown of explosive materials due to the extremely intense electric fields present in laser radiation would offer other interesting possibilities.

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TABLE 1

Initiation energy of pyrotechnic mixture

Energy/Area	Detonation[a]
0 - .0037 J/sq mm	0 0 0 0
.0037 - .0042	0 0 0 0 0 0 0 X
.0042 - .0047	0 0 0 0
.0047 - .0052	0 0 X X X X X X X
.0052 - .0057	0 X X
.0057 - .0062	X X
.0062 +	X X X X

$$\mu = \text{mean} = .0053 \text{ J/sq mm}[b]$$

$$\sigma = \text{standard deviation} = .0015 \text{ J/sq mm}$$

$$\mu + 2\sigma = .0083 \text{ J/sq mm}$$

$$\mu - 2\sigma = .0022 \text{ J/sq mm}$$

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[a] Each experiment is characterized in the following manner:

    X = ignition
    O = no ignition

[b] For an explanation of the method of calculation see page 7.

TABLE 2

Initiation energy of PETN using free-running laser

Energy Range	Detonation[a]
.0795 - .1000 J/sq mm	O X
.1001 - .1260	O
.1261 - .1590	O
.1591 - .2000	O X X
.2001 - .2510	O X
.2511 - .3160	X X
.3161 - .3980	X

$$\mu = .1486 \text{ J/sq mm}$$
$$\mu + 2\sigma = .5035 \text{ J/sq mm}$$
$$\mu - 2\sigma = .0439 \text{ J/sq mm}$$

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[a]Each experiment is characterized in the following manner:
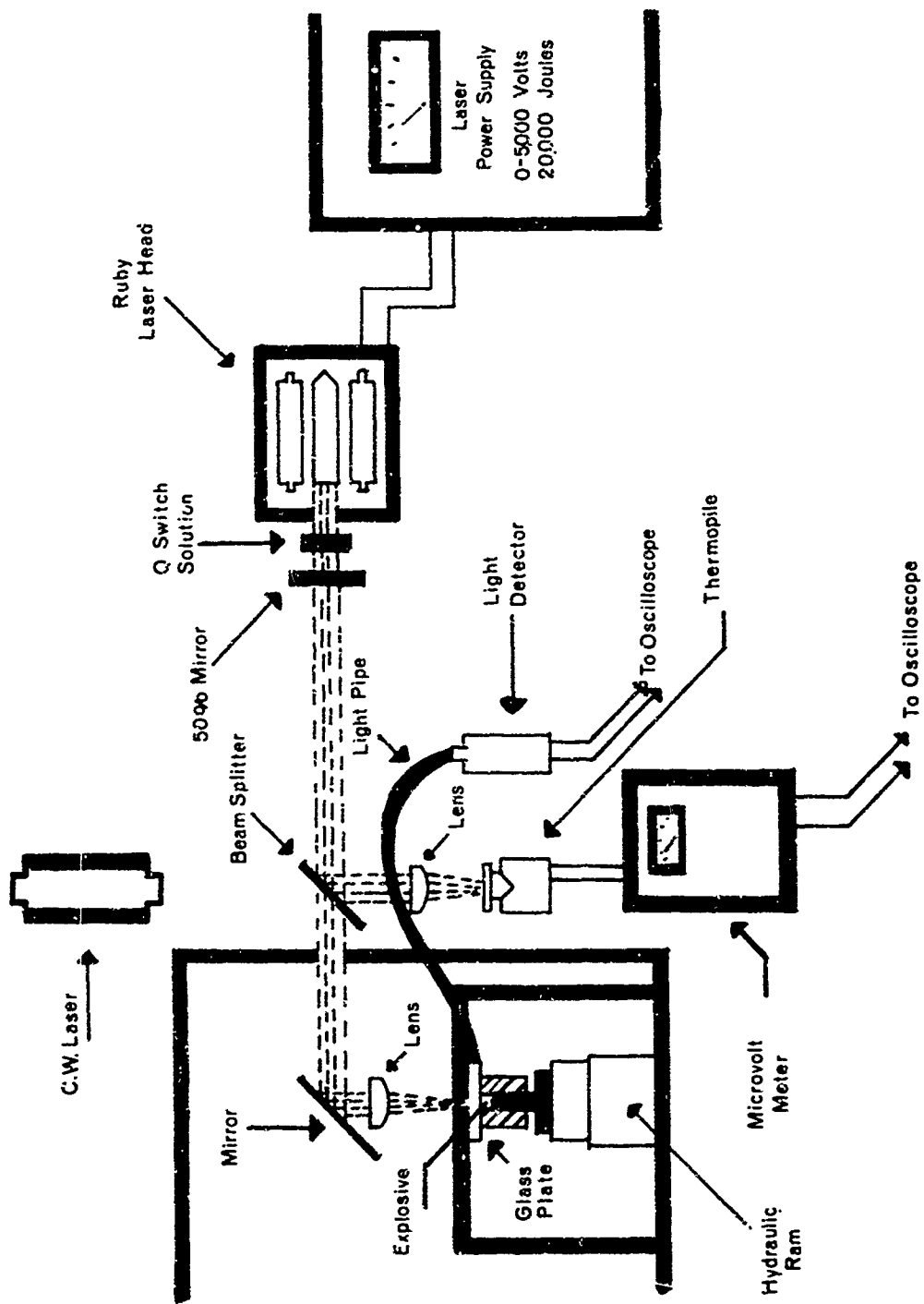
X = ignition

O = no ignition

TABLE 3

Initiation of PETN using Q-switched laser

Energy Range	Detonation[a]
.0016 - .0025 J/sq mm	O
.0026 - .0039	O
.0040 - .0063	O O O O O O
.0064 - .0100	O O O O
.0101 - .0159	O O O O X
.0160 - .0251	O O O O O X
.0252 - .0399	X
.0400 - .0631	X
.0632 - .1000	X
.1001 - .1590	
.1591 - .2520	X

$$\mu = .025 \text{ J/sq mm}$$
$$\mu + 2\sigma = .080 \text{ J/sq mm}$$
$$\mu - 2\sigma = .008 \text{ J/sq mm}$$

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[a]Each experiment is characterized in the following manner:

X = ignition

O = no ignition

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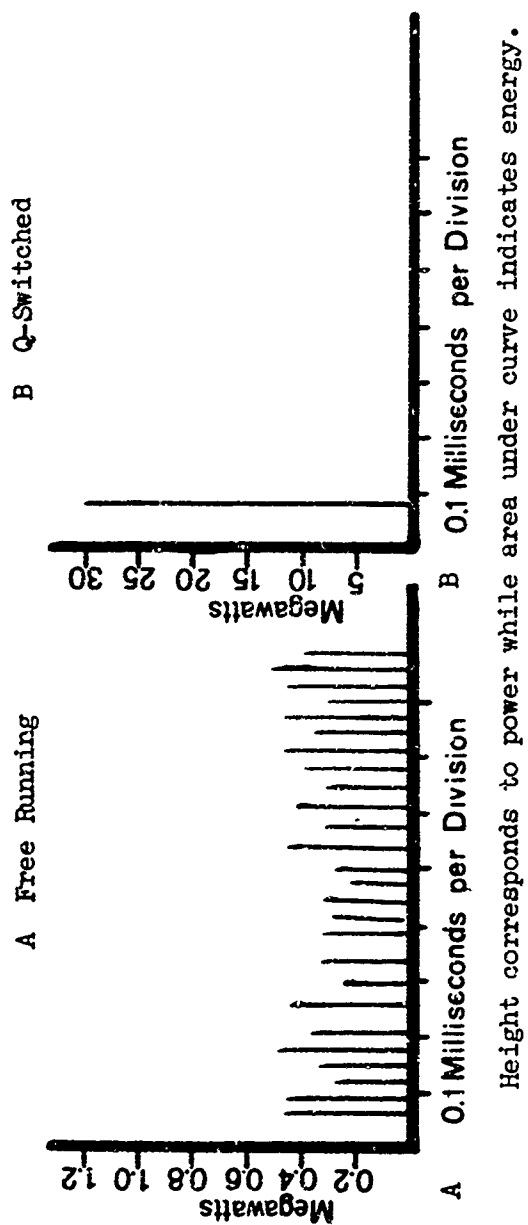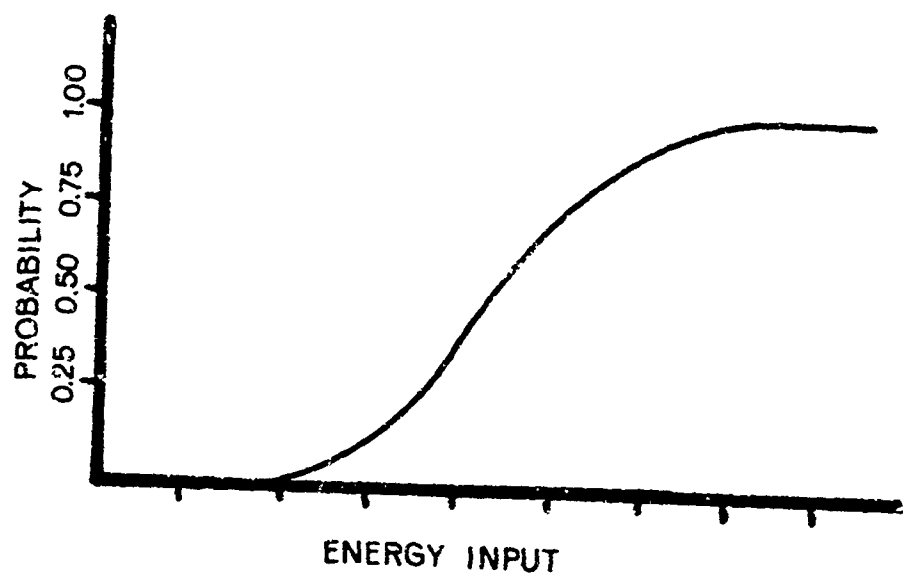Fig 1   Experimental setup for laser initiation of explosives

A Free Running

B Q-Switched

A 0.1 Milliseconds per Division

B 0.1 Milliseconds per Division

Height corresponds to power while area under curve indicates energy.

Fig 2   Laser output

Fig 3   Energy threshold of detonation
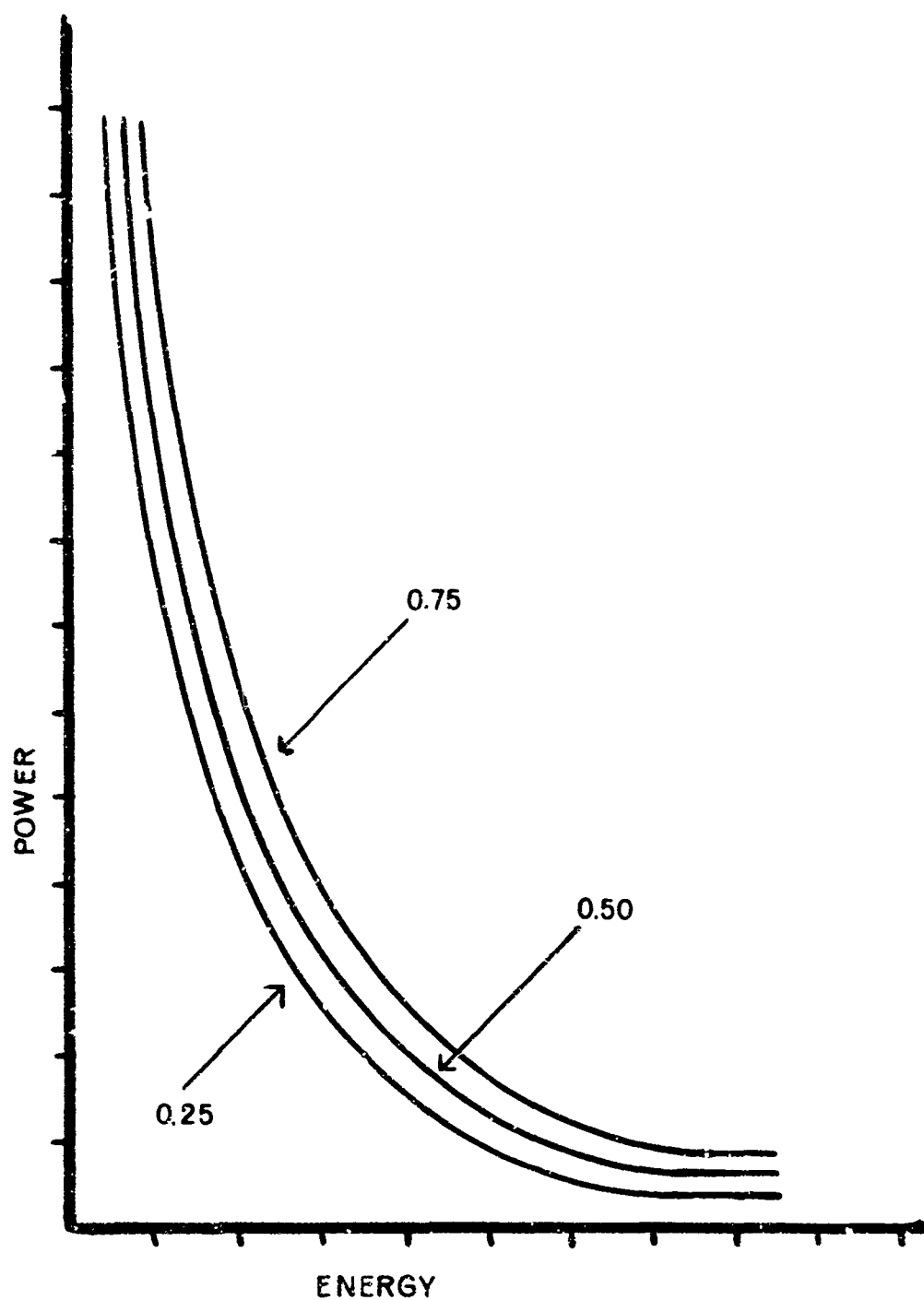
Fig 4   Bivariate probability of initiation

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY

13 ABSTRACT

An experimental investigation was conducted to determine the feasibility of directly detonating secondary explosives by means of radiation from a ruby laser (6943A). The secondary explosives included PETN, HMX, RDX, and tetryl. Most of the effort was devoted to a statistical evaluation of the initiation energy required for PETN. For the most part, powdered explosives were used; however, a limited effort also was expended on large single crystals. The use of a light guide as a means of transporting energy was also examined. It was established that although a highly sensitive mixture can be detonated through a light guide, the attenuation of the radiation is too great to make this method practical for secondary explosives. A bivariate dependence of the probability of initiation on both power and energy is indicated. The effectiveness of the experimental techniques of power evaluation was, however, limited by the speed of the equipment used.

DD FORM 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Laser radiation						
Initiation of explosives						
Secondary explosives						
PETN						
HMX						
RDX						
Tetryl						
Light guide						
Q-switched laser						
Free-running laser						
Monochromatic radiation						
Explosive sensitivity tests						
Ruby laser						